

Applications and Extensions of the Method of Ordered Multiple Interactions

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LONG-TERM GOALS

The primary long term goals of this research is to develop a mathematical technique that will provide analysts with the capability to predict the scattering from ocean and terrain surfaces under the condition of low grazing angle incidence illumination. A secondary goal is to be able to include atmospheric refractivity profiles so as to be able to account for wave refraction particularly in the forward direction. Yet another secondary goal is to provide, where possible, scientific guidelines as to the causes of the dominant behavior to be expected for low grazing angle scattering from the ocean surface.

OBJECTIVES

The scientific objective of this study is to provide insight into and understanding of the complex electromagnetic scattering processes that take place on a rough surface such as the ocean through rigorous modeling, realistic simulation, and efficient computation of the scattering situation. The technology objectives are improved ship defenses, enhanced radar operations during periods of high surface clutter, better remote sensing methods and techniques.

APPROACH

The approach to be followed during this study centers on extending and enhancing a technique developed, in part, under a previous ONR grant. This technique reorders the integral equation describing the electromagnetic current induced on a rough surface by an incident field in such a way that the new equation more nearly replicates the actual physics of the on-surface scattering processes; hence, the name Method of Ordered Multiple Interactions (MOMI). The solution of this reordered equation is, from a computational point of view, significantly more efficient than a standard method of moments technique. This is because it neither requires storage of the impedance matrix resulting from the discretization of the current integral equation nor does it require matrix inversion in determining the discretized current. These two attributes of the technique make it one of the few that is tractable for the low grazing angle incidence geometry.

WORK COMPLETED

We have found certain limitations associated with the use of a tapered incident field in numerical scattering and propagation simulations. Criteria for the beam waist choice have been formulated that

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assure valid simulation results. The cautions to be exercised when using approximate Gaussian-like tapered field in the propagation context have been delineated.

A capability to generate one-dimensional time evolving-rough surfaces with ocean-like roughness spectrum has been developed. Also, a physical model that accounts for hydrodynamic wave interaction effects has been implemented and added to surface generation routines.

We have developed a numerical technique to calculate Doppler spectra of signals scattered from time-evolving ocean-like surfaces. It is based on the numerical solution to the Magnetic Field Integral Equation (MFIE) using the Method of Ordered Multiple Interactions (MOMI) and provides exact calculations of such spectra for one-dimensional surfaces.

An exact and numerically tractable analytical/numerical boundary integral equation model for analyzing the combined effect of surface roughness and medium refractivity on scattering and over-terrain propagation has been fully developed. The Green's function (medium propagator) for a specific ducting environment has been derived using asymptotic techniques. The MFIE involved in the model was solved efficiently via MOMI. Forward scattering results based on this model were used to study the accuracy of the very popular parabolic wave equation (PWE) model. Simulation results based on our model also facilitated the study of ducting effects on LGA backscatter. These effects are certainly to be taken into consideration when LGA radar targeting over the ocean surface is carried out.

RESULTS

Part of our research effort continued to be directed towards studying the factors affecting the validity of numerical scattering calculations at low grazing angles (LGAs). We discovered that one such factor is the taper used with the incident field. In numerical simulations, it is common to use a tapered incident field to guard against so-called "edge effects" associated with a finite length of the simulated surfaces. Probably, the simplest and the most popular tapered "incident beam" is a plane wave modulated by a Gaussian taper function. Unfortunately, such an incident field does not exactly satisfy the Helmholtz wave equation. An improved Gaussian taper which provides better agreement with the wave equation (though still being approximate) was proposed by E. Thorsos (1988). In our scattering simulations that are based on solving the magnetic field integral equation (MFIE) we observed an anomalous jump in the calculated backscattering cross section as the incident angle approaches grazing. We were able to relate these anomalies in cross section to the approximate nature of the Gaussian-like taper and insufficient beam width. The taper-related distortions and anomalies at low grazing incident angles were observed in calculated bistatic cross sections and surface currents as well. Based on these observations, we have proposed a refined criterion that relates the required beam waist to the angle of incidence [1]. We demonstrate that when this criterion is followed the problem with anomalous results at LGA is averted and scattering calculations remain valid. Also, we observed certain self-inconsistencies in the incident field with the Gaussian-like taper that result from its approximate nature and have not been appreciated before. For example, if one uses the approximate expression to define the incident field on a vertical plane and then propagate it to the surface using exact Green's function, the result may differ significantly from what would be predicted by the very same approximate formula when evaluated on the surface. This observed self-inconsistency of the incident field can be a factor in over-surface-propagation simulations. It should also be considered when one performs numerical studies of scattering from objects in the presence of rough surface (e.g. a cylinder above rough surface). In such problems one cannot use the approximate expression for the

incident field to evaluate such a field on the object(s) and on the surface simultaneously. The incident field that fully satisfies Maxwell equations should be used in the problems of this type.

The routines developed for generating time-evolving rough surfaces in conjunction with the MFIE-based numerical solution technique allow us to simulate and analyze the time dependence of signals scattered from ocean-like surfaces and their Doppler spectra. The range of incident angles in such studies can vary from normal to low grazing incidence. These simulations can thus be used to verify approximate analytical models for Doppler spectrum that exist for small to moderate incident angle range; such simulations become a principal tool in analyzing Doppler spectra at LGAs where no analytical models are available. It should be pointed out that this MFIE-based Doppler simulation technique benefited directly from our investigation of factors (like field tapering and discretization) affecting the validity of the numerical MFIE solution at LGA [1], [2]. Indeed, in Doppler simulation it is especially important that both amplitudes and *phases* of scattered signals are correct for *each* surface configuration, and our studies assure this. Our ability to include hydrodynamic interaction effects in surface models allows us to investigate the influence of these effects on the Doppler spectrum and their significance. As far as linear surfaces with the ocean-like Pierson-Moskowitz spectrum are concerned, one interesting result of the simulations is that as the incidence angle approaches grazing, the Doppler spectra of backscattered signals for both vertical and horizontal polarizations become very narrow and centered at frequencies corresponding to Bragg surface components. Inclusion of hydrodynamic interaction effects in the surface model causes a broadening of the Doppler spectra, especially at LGA. Also, we observe polarization-dependent differences in shapes and locations of Doppler spectra for both linear and non-linear surfaces. These issues will be the subject of further investigation.

The other thrust of our research deals with the refractivity effects on the rough surface scattering and the propagation over the rough terrain problems. We believe that the most rigorous formulation of any scattering or propagation problem, which involves a rough surface, is the boundary integral equation formulation. For free space, this formulation is easy to set up and solve numerically due to the fact that the free-space propagator (Green's function) is well known. For ducting environments, however, the medium propagator cannot be derived in closed form. Moreover, the numerical evaluation of such Green's function turns out to be extremely cumbersome due to the oscillatory nature of the integrands involved. Consequently, the only resort appears to be asymptotic techniques. We were able to derive a useful and numerically tractable form of the Green's function of a ducting medium formed by a linear-square refractivity profile and used that in a boundary integral equation regime to study the refractivity effects on scattering from rough ocean surfaces. The asymptotic techniques used in our derivation were the methods of stationary phase and steepest descents. Although the Green's function was derived for a special refractivity profile, we believe that we can use the same methodology mentioned above in conjunction with the WKB method to generalize our results to more realistic refractivity profiles. Simulation results based on our model provide the only benchmark, to our knowledge, against which the validity of the PWE approximation for forward scattering and propagation in ducting environments may be examined [3] & [4]. Using our model in conjunction with some formulas from the theory of geometrical optics, we were able to account for multiple bounces of the predominant specular scattered field from the rough surface [3]. Another very important issue we examined, through numerical simulations based on our model, was the ducting effect on LGA backscatter from ocean-like surfaces. Our model facilitates such investigation through its capability of predicting scattering in all directions, in a ducting environment, including backscatter. The PWE-based models certainly do not provide this capability. Through our simulations, we have noticed that, for a strong refractivity profile, the backscattered field (the field calculated along the vector \mathbf{R} which starts on the surface and points in the

backscattering direction) whose power is supposed to have a $1/|\mathbf{R}|$ (in 2-D problems) dependence in free space, is contaminated by the fields scattered in other near-backscattering directions. We have run numerical simulations of the average of the incoherent backscattered power over multiple realizations (up to 200 realizations) of an ocean-like Pierson-Moskowitz random rough surface for both free space and a ducting environment. We noticed that the average backscattered power level was higher in the ducting environment than free space due to the reason mentioned above [3]. This effect is certainly to be taken into consideration when LGA radar targeting over the ocean surface is performed. It may also be of use in inverse scattering applications where information about the refractivity profile is inferred from the measured backscatter data in ducting environments. Another important issue that we had to deal with during our investigation of the ducting problem is the determination of the suitable tapered incident field to be used in our numerical simulations. In the propagation community, certain tapered fields satisfying the approximate PWE have been proposed. Since our formulation is exact in the sense that it is based on the full Helmholtz wave equation, the appropriate tapered incident field used must satisfy the Helmholtz equation, i.e. it must be Maxwellian. Our numerical simulations show that the Gaussian-like tapered incident field and its modified version attributed to E. Thorsos, which is very popular in the surface scattering community, is not Maxwellian when defined away from the origin. This observation has been exhibited through the numerical simulations in [1]. The analytical derivations documented in [1] further assess the above fact. A fully Maxwellian tapered incident field was proposed for LGA rough surface scattering applications [1].

IMPACT/APPLICATION

Probably the most important near term impact of this research relates to the understanding of what surface roughness features are most important in what angular ranges of the scattering process. For example, this knowledge is absolutely essential in accomplishing remote sensing using either high- or low-resolution sensors. In addition, it is absolutely essential to ship protection using beyond-visual-range sensors since an accurate understanding of exactly what is giving rise to the clutter is a critical component in developing alternate or complementary sensors. Finally, the impact of this research upon personnel training should not be underestimated. If the scattering from the ocean or land surfaces can be accurately understood and modeled, it will be possible to build trainers and simulators to faithfully replicate at-sea conditions without the expense of go to sea!

TRANSITIONS

None

RELATED PROJECTS

We presently have an Army Research Office sponsored project to investigate and develop better over-terrain propagation prediction methods. Although the primary emphasis of the ARO work is to develop methods to account for surface features such as edges, wedges, and vertices there is clearly a linkage to this ONR-sponsored work.

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